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MAGNET ASSEMBLY

The invention relates to a magnet assembly for use in enabling a NMR (nuclear magnetic resonance) process to be performed on an object.

Conventional NMR requires the generation of a substantially uniform magnetic field in a working (or homogeneous) region. An object to be subject to the NMR process is located in the homogeneous region and is exposed to a RF pulse which causes an NMR signal to be issued in the usual manner from the object and this is then detected. Magnetic field gradients can be used to map the frequency and phase of the NMR signal to the location within the region from which the NMR signal is obtained.

NMR processes have found particular application in magnetic resonance imaging (MRI), particularly whole body imaging, but are also used in a wide variety of other applications including spectroscopy.

One problem with conventional NMR systems is that the homogeneous region is located fully within the magnet assembly itself and so for conventional human body MRI, a patient has to be located within the assembly. Various proposals have been made for open-access assemblies in which the homogeneous region is projected outside the magnet assembly. The problem with these new magnet assemblies is that in the field of MRI, users are very reluctant to replace their existing equipment by new, relatively untested equipment.

In accordance with the present invention, we provide a magnet assembly comprising first and second sets of coils for generating respective magnetic fields, wherein the coils are constructed and arranged such that under working conditions, a first homogeneous region can be generated within the envelope defined by the magnet assembly and a second homogeneous region can be generated outside the envelope, the resultant magnetic field in each region being

sufficiently homogeneous to enable a NMR process to be performed on an object in the region.

With this invention, we have recognised that the magnet assemblies used for NMR processes generate a fringe magnetic field and that instead of trying to reduce this as is conventionally attempted, this can be utilized to create a second homogeneous region. Many magnet assemblies are actively shielded so as to reduce the fringe field but even with these it is still possible to generate an external homogeneous region, at least utilizing the axial fringe field. The advantage of this is that the user is presented with a familiar structure which continues to generate the conventional, first homogeneous region within the assembly but has the additional benefit of generating the second homogeneous region for open-access.

In some cases, the two homogeneous regions can be generated alternately which has the advantage that the first homogeneous region will be identical with its form if the second set of coils have not been provided (or actuated). Alternatively, the two homogeneous regions could be generated simultaneously which would simplify operation of the assembly although there would be a slight reduction in the size of the first homogeneous region compared with its size when the second set of coils was not operated (or present).

The first set of coils can take a conventional form and typically will define a solenoid and may be actively shielded.

The second set of coils are typically nested and preferably substantially co-planar to reduce the volume of their envelope. In general, at least two of the coils of the second set will carry working currents in opposite senses in order to generate the second homogeneous region.

Typically, the second set of coils will comprise at least two pairs of coils and in the preferred arrangement, in the first homogeneous region each pair of coils generates a substantially zero first order magnetic field

gradient and substantially equal second order magnetic field gradients of opposite senses.

It may be possible in certain circumstances for one coil from each pair to be coalesced with the result that a total of three coils is needed.

It should also be recognised that although we have referred to separate coils in the above discussion, each set of coils could be connected in series.

The coils themselves are typically superconductive and preferably at least the second set of coils is made from high temperature superconductor. Alternatively, both sets of coils could be made of conventional low temperature superconductor and then housed within respective, or preferably the same, cryostats.

By defining the magnet assembly as having two sets of coils, it will be possible to form the second set of coils as a self-contained unit so that they can be separated from the first set of coils without compromising the operational integrity of the first set of coils. Thus, the second set of coils provides a "bolt-on" to a conventional magnetic resonance magnet assembly. In this connection, we mean that the second set of coils could be detached from the first set of coils without having to purge the cryostat containing the first set of coils.

In practice, however, it will usually be more efficient to construct the first and second sets of coils together, particularly if they are to be housed within the same cryostat.

Typically, the homogeneous regions will be substantially spherical but it would also be possible to construct the second set of coils such that the second homogeneous region is substantially disk shaped and has a magnetic field gradient in the axial direction. This enables slice selection to be more easily achieved without compromising the open access with obtrusive gradient coils.

In order to balance forces within the magnet assembly, preferably an additional set of second coils located

adjacent an opposite side of the first set of coils to the one set of second coils.

Some examples of magnet assemblies according to the invention will now be described with reference to the accompanying drawings, in which:-

Figure 1 is a schematic cross-section through an example of a magnet assembly;

Figures 2 and 3 illustrate the axial field profile and field contour respectively for an unshielded based example;

Figures 4 and 5 are similar to Figures 2 and 3 respectively but for a self-shielded example;

Figure 6 illustrates the variation of B1 and B2 for a double homogeneous region system;

Figure 7 is a plot of R and S;

Figures 8-12 plot B_2/B_1 at b_2 against a_2 for systems which satisfy this condition, for various values of a_1, α_1 and α_2;

Figure 13 is a view similar to Figure 1 but for one of the systems illustrated in Table 1 below;

Figures 14-17 show the axial profiles for the systems referenced 1, 3, 5 and 6 respectively;

Figures 18 and 19 show the axial field profile for this system, and the difference between it and the non-gradient system; and,

Figures 20A and 20B illustrate circuits including the main magnet and accessory coils during and after energisation respectively.

Figure 1 illustrates the general structure of a magnet assembly according to the invention. Thus, a main magnet 1, typically a solenoid, is located adjacent a set of nested accessory coils 2 which are coaxial with the magnet 1. As will be explained below, the magnet 1 and coils 2 can be activated in a variety of ways so as to generate (not necessarily simultaneously) a first homogeneous region 3 centred within the magnet 1 and a second homogeneous region 4 located externally of the envelope of the overall assembly.

The main magnet 1 and accessory coils 2 will be made from superconducting material. Both could be made from low temperature superconductor and they could be located within the same or respective cryostats (which are not shown in Figure 1 for clarity). The accessory coils 2 could instead be made of high temperature superconductor and again could be located within the same or a different cryostat from that of the main magnet 1. The main magnet 1 and accessory coils 2 could be separable without compromising the integrity of the main magnet 1 which can be allowed to continue to operate, providing the two are self-contained. In general, however, the main magnet 1 and accessory coils 2 will be located together.

1 Inhomogeneous magnet central field region 3

The use of a set of accessory coils with two examples of conventional MRI magnets has been studied.

1. Unshielded 1.5T magnet (axial length 1.75m)
2. Self-shielded, short 1.0T magnet (axial length 0.975m)

The accessory windings 2 are assumed to occupy a space 100mm thick and to be spaced 75mm from the end of the magnet windings. The working or homogeneous volume 4 is assumed to be 250mm from the accessory windings 2.

In both cases, an accessory coil was found which cancelled the 1st and 2nd order axial gradients at the working volume, producing plateau regions in the profile of the fringe field. Additional coils to cancel higher order gradients would be possible, and would not greatly affect the conclusions with respect to field strength and forces.

Unshielded 1.5T magnet

The axial field profile and field contour map are shown in Figures 2 and 3. In Figure 2, the centre of the second homogeneous region 4 is shown at 5. Z=0 corresponds to the axial centre of the magnet 1. In Figure 3, lines 6-

8 indicate contours at 2.0E-04, 1.0E-04 and 2.0E-05 tesla respectively.

The field strength in the region 4 is 0.2 tesla (13% of the magnet's central field) and the axial force between the accessory coil 2 and the magnet 1 is 81.75 tonnes. The accessory coil 2 has 618600 Ampere-turns at a mean radius of 444mm.

Self-shielded, short 1.0T magnet

Figures 4 and 5 show equivalent plots to Figures 2 and 3. The field strength in the region 4 is 0.1 tesla (10% of the magnet's central field) and the axial force between the accessory coil 2 and the magnet 1 is 141.74 tonnes. The accessory coil 2 has 613760 Ampere-turns at a mean radius of 515mm. In Figure 5, lines 9-11 illustrate contours at 1.0E-04, 5.0E-05 and 1.0E-05 tesla respectively.

2 Homogeneous magnet central field region 3

The above showed that it was possible to produce an "external field" region 4 beyond the end of conventional MRI magnets 1. The examples, which used a single coil 2, although producing an external homogeneous region 4, destroyed the field uniformity at the centre of the magnet 3. This means that the two regions 3,4 could not be used at the same time. Because of the coupling of the accessory set 2 with the main magnet 1, energisation of the accessory 2 requires that the main magnet 1 is also put on its power supply.

A further improvement is to have both regions 3,4 available simultaneously, so that the combined system would only need energising once.

This can be achieved by finding a system of accessory coils 2 which

1. Cancel the gradients at the end of the magnet 1 so as to produce an external homogeneous region 4, while

2. Not producing inhomogeneities at the centre of the magnet which cannot be corrected by a standard shim set as would be provided with a MRI system.

As an example, the unshielded 1.5 tesla magnet described previously is used. The target is to find a set of accessory coils 2, essentially co-planar and positioned 1 metre from the magnet centre which produces a field which has no first or second order gradients at the centre of the region 3, or at the external field volume 4, about 1.3 metres from the magnet centre. Higher order gradients should be sufficiently small to be manageable with shim-coils. The arrangement is illustrated in Figure 1, with $b_1 = 1.0$m and $b_2 \approx 0.3$m.

Thus we seek a system that produces no 1st or 2nd order gradients (B1,B2) at b_1 while producing a specified ratio of 2nd to 1st order gradients (B2/B1) at b_2. In this example, the ratio is about -1.8577 at $b_2 = 0.3$m and its most negative value is -2.41 at $b_2 = 1.65$m. See Figure 6.

To achieve this, the accessory coils system 2 consists of four coils. These are grouped in two pairs. Each pair produces zero 1st order gradient (B1) at b_1 and the second order gradients (B2) produced by the pairs are equal and opposite. The dimensions are then chosen to produce the correct ratio of B_2/B_1 at b_2 and the strengths adjusted to cancel the magnet gradients at this point.

To make the calculation (relatively) easy, the coils are represented as single turns, characterised by a radius, a_1, a_2, a_3, a_4 and a relative strength n_1, n_2, n_3, n_4. The single-turn coils can be replaced with coils of distributed current density whose effective centroids are at the positions occupied by the single-turn coils.

Coils 1 and 2 are members of one pair, and 3 and 4 are members of the other pair. We also use the ratios $a_1 = a_2/a_1$ and $a_2 = a_4/a_3$.

For a single turn, the gradients, in units of $A/m^{order+1}$, are given by Equations 1-4.

A pair of coils then produces no first order gradient at position b on the axis when Equation 5 is satisfied.

The total second order gradient of the pair is given by Equation 6.

These functions are shown plotted against α and a for b = 1m in Figure 7.

We can now see that it is possible to choose two pairs of coils with different values of α and choose their relative strengths so that the second order gradients cancel. There is an infinite number of pairs of pairs for which this is possible, so all we need to do is to find some which also have the correct ratio of B_2/B_1 at b_2. The condition for zero B_1 and zero B_2 at the magnet centre is given by Equation 7 where m is the strength of the second pair relative to the first.

Figures 8 to 12 plot B_2/B_1 at b_2 against a_2 for systems which satisfy this condition, for various values of a_1, α_1 and α_2.

It can be seen that for most of these curves, the required value of -1.8577 exists, although for the smaller values of a_1 and a_2 the steepness of the curves in this region implies a high accuracy of a is required.

Using this method, some examples have been calculated. Table 1 shows the radii (a) and relative strengths (n) for coils 1 to 4, and the field strengths in the two homogeneous regions 3,4 (original central field was 1.5 tesla). The last two columns show the radii of the homogeneous volumes, being the radius at which the third order gradients contribute 100 ppm i.e. volumes which are sufficiently homogeneous to enable an NMR process to be performed on an object in the region.

Table 1

ref		coil 1	coil 2	coil 3	coil 4	$B_0(b_1)$ Tesla	$B_0(b_2)$ Tesla	$r_0(b1)$ m	$r_0(b2)$ m
1	a (m)	0.300	0.600	0.3719	0.4463	1.497	0.411	0.172	0.014
	n (Aturns × 10^5)	3.4150	-1.4845	-10.115	8.0018				
2		0.300	0.900	0.3763	0.5644	1.490	0.382	0.135	0.015
		1.2769	-0.5038	-2.8267	1.8011				
3		0.600	0.900	0.6317	0.7580	1.462	0.311	0.097	0.019
		7.7195	-7.0107	-17.145	16.000				
4		0.600	1.800	0.559	1.118	1.305	0.139	0.077	0.015
		1.3267	-2.5299	-2.2001	2.1163				
5		0.900	1.350	0.614	0.7368	1.424	0.267	0.088	0.018
		1.1151	-1.5050	-3.0703	2.8334				
6		0.900	2.700	0.532	1.064	1.126	-0.040	0.072	0.010
		0.6110	-3.0480	-1.0293	0.916				

Figure 13 illustrates the arrangement of example 2 from the Table. Figures 14-17 show the axial profiles for the systems referenced 1, 3, 5 and 6 respectively.

The above analysis has described systems which produce an approximately spherical volume of field homogeneity. For the external field region 4, it can be advantageous to have a fixed first-order Z-gradient, to be used in slice selection. This avoids the use of Z-gradient coils which would obtrude on the access to the homogeneous region. In this the homogeneous volume is disk-shaped, with the radius of the disk determined by the third-order gradient.

The calculation proceeds as follows:

If the required Z-gradient at b_2 is G_z, then the system of coils is chosen to have the ratio of second to first order gradients of $B_2/(B_1-G_z)$. The strength is then chosen to give the required value of G_z. An example is set out in Table 2.

Table 2

ref		coil 1	coil 2	coil 3	coil 4	$B_0(b_1)$ Tesla	$B_0(b_2)$ Tesla	$r_0(b1)$ m	$r_0(b2)$ m	G_z Tm^{-1}
2b	$a\,(m)$	0.300	0.900	0.37613	0.56420	1.490	0.3856	0.135	0.015	-0.019
	$n\,(Aturns \times 10^6)$	1.2509	-0.49387	-2.7734	1.7669					

Figures 18 and 19 show the axial field profile for this system, and the difference between it and the non-gradient system.

Figure 20 illustrates the circuits in which the magnet 1 and accessory coils 2 are located. As can be seen in Figure 20A, each has its own power supply 20,21 respectively. In the case of the magnet 1, this is connected in parallel with a switch 22. During energisation, the two supplies 20,21 are switched on while the switch 22 is open. The switch 22 is then closed and the magnet 1 will continue to operate in persistent mode while power continues to be supplied from the power supply 21 to the coils 2 (Figure 20B).

In practice, energising the accessory coils 2 would require either

- putting the main magnet 1 back on its power supply, or

- having a second accessory coil at the other end of the magnet so that the net coupling to the magnet was zero. (However, this would double the force problem - see below), or

- designing and setting up a system such that the main magnet 1 and the accessory coils 2 could be used together, and so both could be left permanently energised.

It should be noted that the force between the accessory coils 2 and the magnet 1 is substantial. The

force acting on the magnet's cryostat could be eliminated by a symmetrical arrangement of accessory coils at both ends.

EQUATIONS

(1) $$B_0(a,b) = \frac{\mu_0 a^2}{2(a^2+b^2)^{3/2}}$$

(2) $$B_1(a,b) = \frac{-3\mu_0 a^2 b}{2(a^2+b^2)^{5/2}}$$

(3) $$B_2(a,b) = \frac{15\mu_0 a^2 b^2}{2(a^2+b^2)^{7/2}} - \frac{3\mu_0 a^2}{2(a^2+b^2)^{5/2}}$$

(4) $$B_3(a,b) = \frac{-105\mu_0 a^2 b^3}{2(a^2+b^2)^{9/2}} + \frac{45\mu_0 a^2 b}{2(a^2+b^2)^{7/2}}$$

$$\frac{n_1}{n_2} = -\frac{a_1^2\,\left(a_2^2+b^2\right)^{5/2}}{a_2^2\,\left(a_1^2+b^2\right)^{5/2}} = -\frac{1}{\alpha^2}\frac{\left(\alpha^2+\beta^2\right)^{5/2}}{\left(1+\beta^2\right)^{5/2}} = R(\alpha\,\beta)$$

Equation 5

$$S(a, b, \alpha) = B_2(a, b) + R(\alpha b/a) \cdot B_2(\alpha a, b)$$

Equation 6

$$S(a_1, b_1, \alpha_1) = mS(a_3, b_1, \alpha_2)$$

Equation 7